Subscale Test Methods for Combustion Devices

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Outline

- Motivation for Scaled Experiments
- Brief Scaling History
  - Steady-State Combustion
  - Combustion Stability
  - Life Prediction
- Scaling Approaches Presently Used at Purdue

Background

- Stated goals for long-life LRE's have been between 100 and 500 cycles
  - Inherent technical difficulty of accurately defining the transient and steady state thermochemical environments and structural response (strain)
  - Limited statistical basis on failure mechanisms and effects of design and operational variability
  - Very high test costs and budget-driven need to protect test hardware (aversion to test-to-failure)
- Ambitious goals will require development of new databases
  - Advanced materials, e.g., tailored composites with virtually unlimited property variations
  - Innovative functional designs to exploit full capabilities of advanced materials
  - Different cycles/operations
- Subscale testing is one way to address technical and budget challenges
  - Prototype subscale combustors exposed to controlled simulated conditions
  - Complementary to conventional laboratory specimen database development
  - Instrumented with sensors to measure thermostructural response
  - Coupled with analysis

SSME Film Cooling Analysis

- Configuration
  - Propellant = LOX + LH2 with O/F = 6.02
  - M_dot_LOX = 64,000 liter/min
  - M_dot_LH2 = 178,000 liter/min
  - M_dot_coolant for regen cooling = 29.06 lb/sec
- Chamber condition
  - Pc = 3300 psi
  - Tc = 3500 K (5840 F)
  - D_throat = 10.88”
  - E = 77
- Cooling channel
  - Wall thickness = 0.03”
  - Width = 0.04 “
  - Height = 0.12 “
  - Pressure_throat = 3851 psi
- Thermal condition at throat
  - Heat flux = 80 Btu/in^2-s
  - hg = 58000 W/m^2-K
  - Twg = 1100 F
- Wall adiabatic temperature
  - Taw = Tr - η(Tr-Tco)

    Where Tr = recovery temperature

    η = film cooling efficiency

    Tco = initial coolant temperature

- Current near wall O/F ratio
  - q_dot = hg(Taw-Twg)

    Where q_dot = 80 Btu/in^2-s

    hg = 58000 W/m^2-K

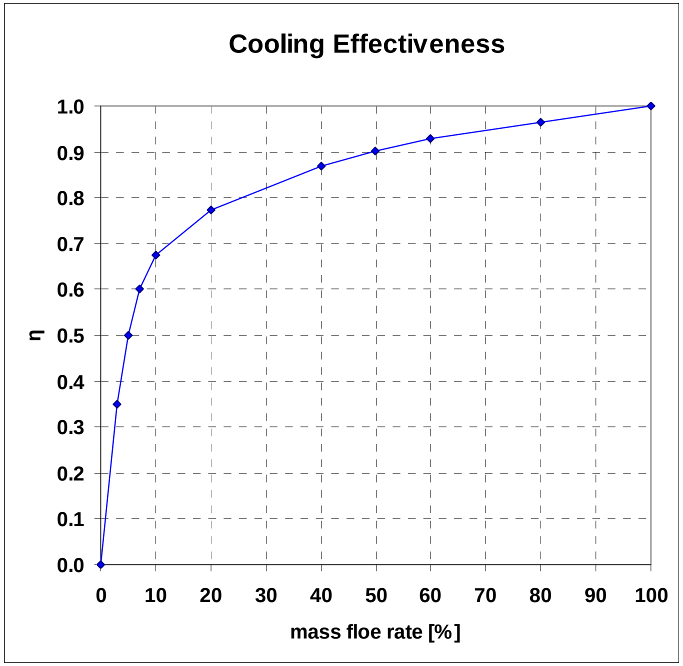
    Twg = 1100 F

    ➔ Taw = 3125 K

    η = 0.5

    ➔ Tco = 2750 K

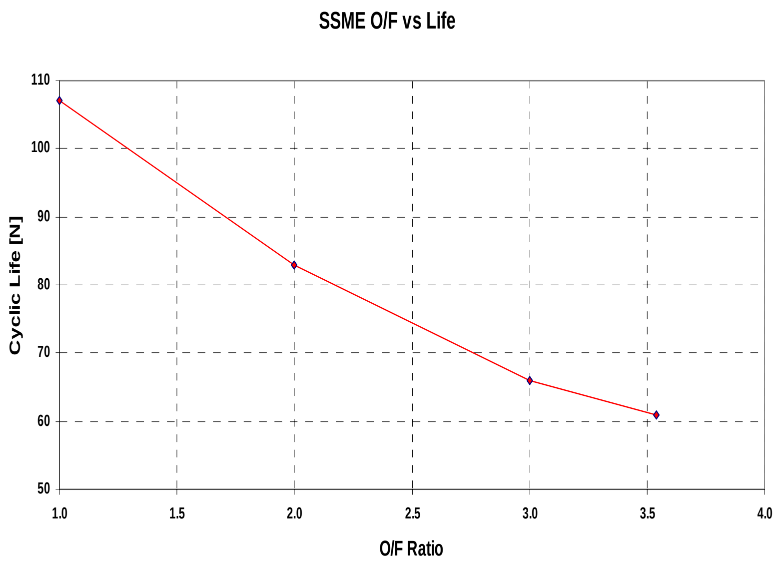
    ➔ O/F_nw = 3.54 from Flame temperature vs O/F ratio chart

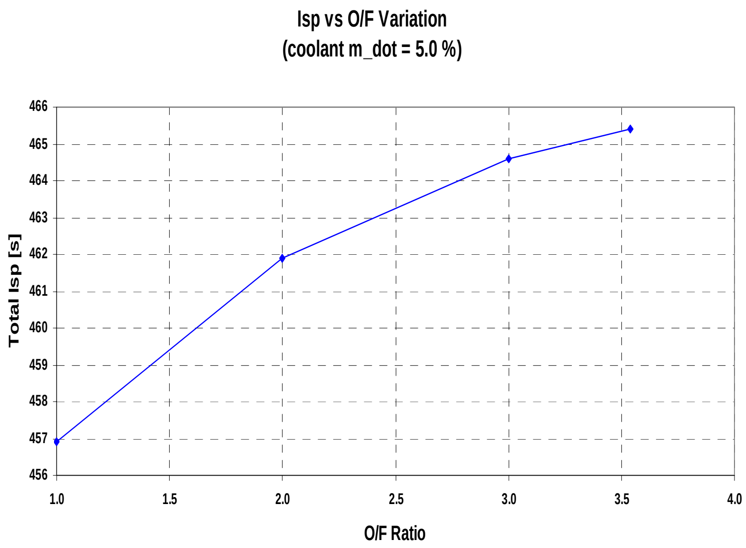


SSME Film Cooling Analysis

- Current film cooling condition
  - O/F_nw = 3.54
- Parametric study with fixed film flow rate (5 %)

  *Porowski et al. method (AIAA Journal Vol. 2 No. 2, 1985)
  - O/F_nw change = 3.54 → 1.0
  - Life change = 61 → 107 (75.4% increase)
  - Isp change = 465 → 457 (1.83 % decrease)

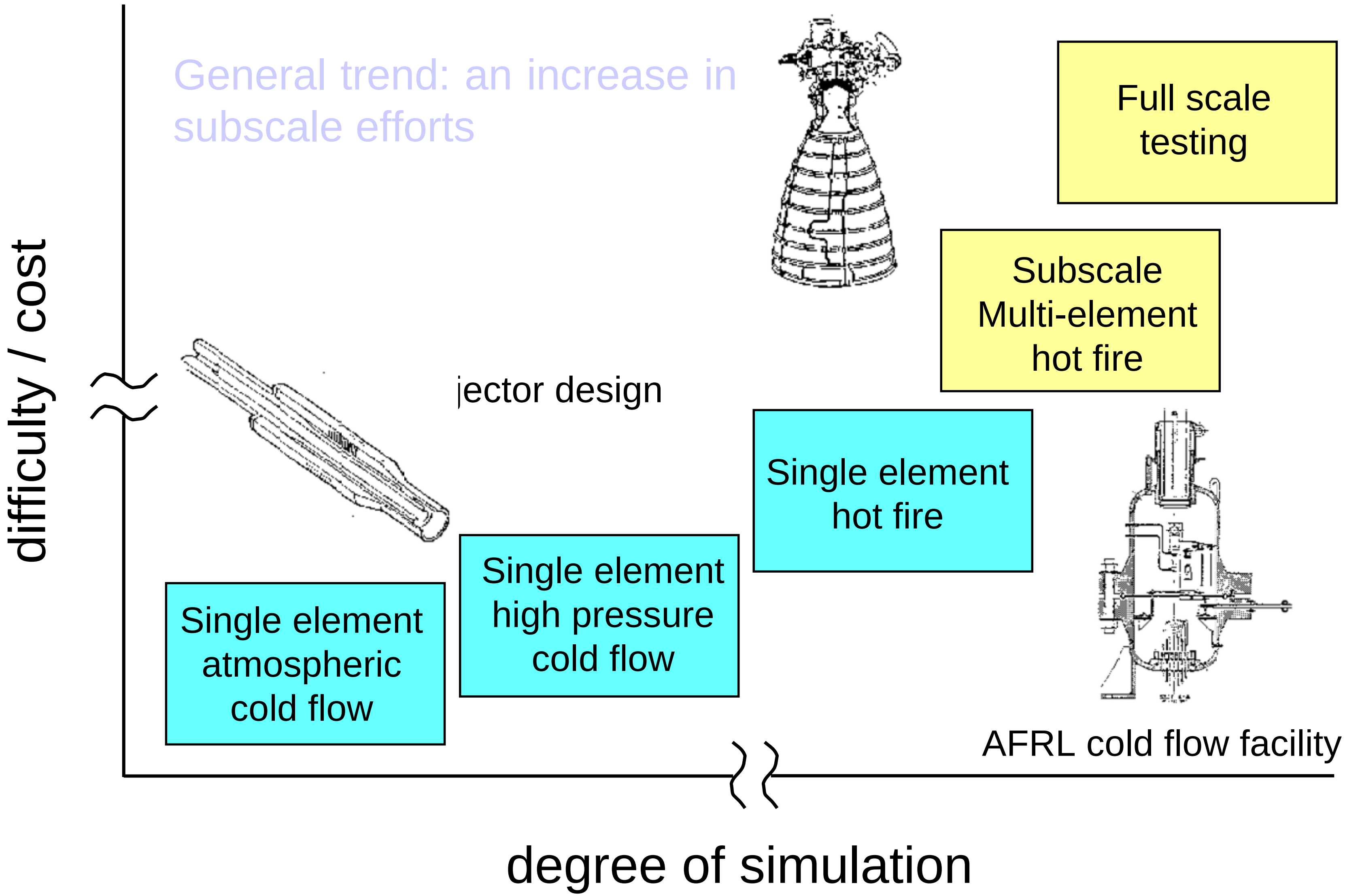




Scaling Objectives and Approaches

- Combustor characterization is goal
  - Validation data for design analysis models
  - Assess innovative functional design, materials, operation
  - Investigations into specific physics
- Single element, multi-element, 40K, 250K
- Cold flow and hot fire
- Performance, heat transfer, life, stability
- Experimental objective needs to define scaling approach and measurement
  - Well-instrumented combustors linked to analysis
  - Thrust level and number of elements
  - Element scaling and configuration

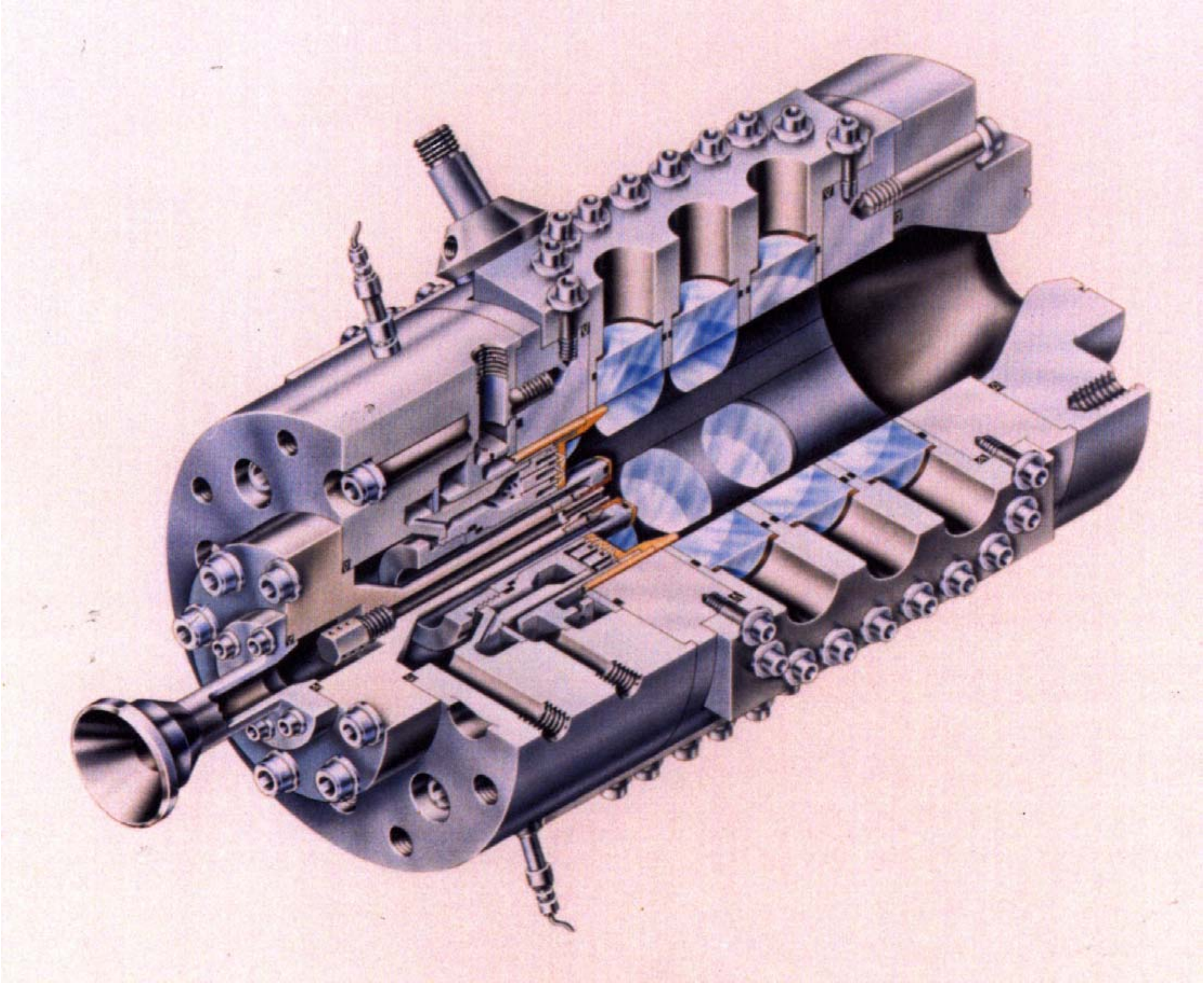
Hierarchy of injector experiments



Brief History of Scaling in the US – Steady State Combustion

- JPL studies of mixing efficiencies of impinging jets
- Bell Aerospace/AFRL holographic and shadowgraphic studies of combusting flows
- Rocketdyne development of LISP methodology for SDER
- Aerometrics development of PDPA
- Rocketdyne studies of flameholding behind LOX post
- PSU measurements of chemical species in HO combustors
- AFRL studies of supercritical jets

Single Element Test Chamber



Stability Scaling

- Simulation of chamber dynamics in subscale configuration is very difficult
  - Acoustic frequencies scale as ~ 1/d
  - Pressure *v* velocity sensitivity
- Scaling approaches
  - Wedges, T-burners, 2-d chambers
  - 1T = 3T scaling
- Single element rarely used in US, but is more typical in Russia

Experimental Approach of Bazarov

This facility screened Injector elements for Liq/liq and gas/liq Injectors for over 20 Years (1965-85)

Typical Pc = 750 psi, Total flowrate of 5 lb/s

‘self-oscillation’ and response to pulsations measured

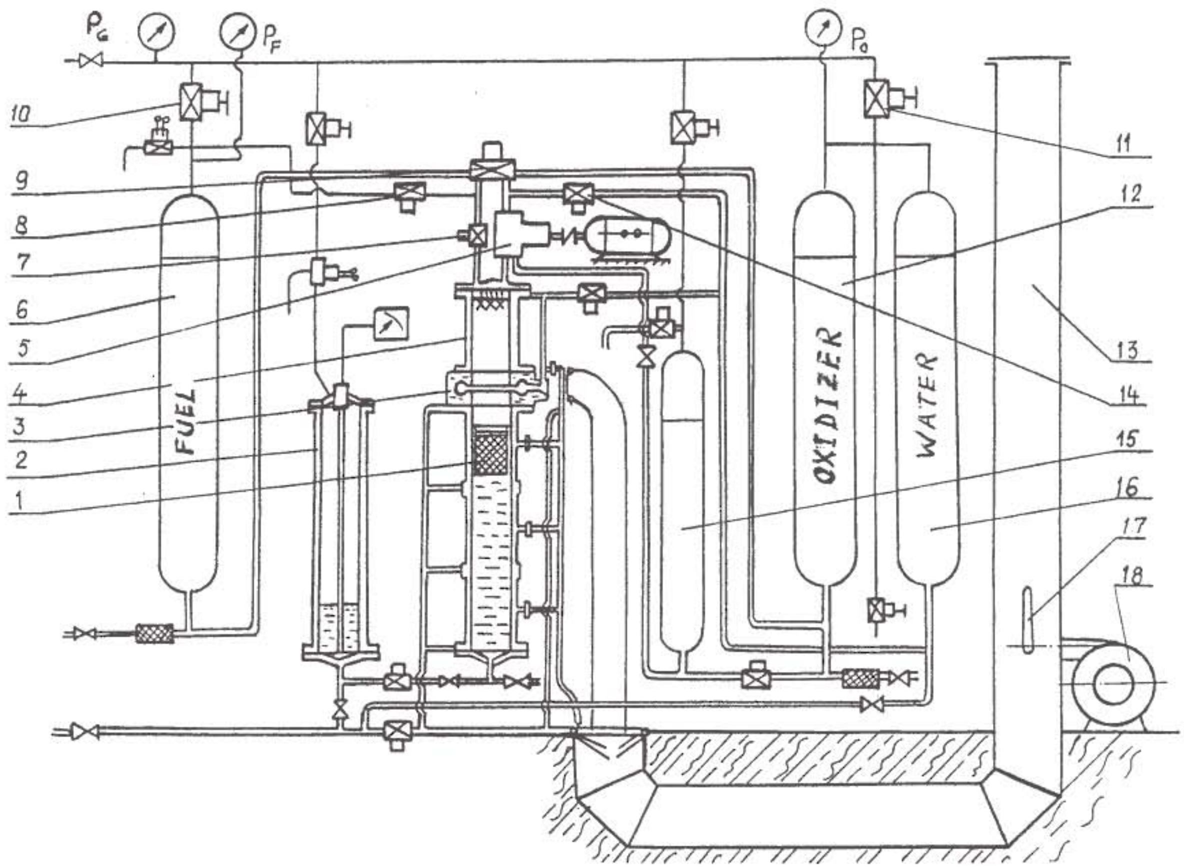


Fig.8 Pneumatic and hydroulic scheme of fire stand
1-piston, 2-measuring vessel, 3-nozzle collector, 4-combustion chamber, 5-pulsator, 6-fuel tank, 7-time delay valve, 8-blow through valve, 9-main bi-propellant valve. 10,11-pressurising gas reductors, 12-oxidizer tank, 13-exhaust tubes, 14-water valve, 15-oxidizer return tank, 16-pressurised water tank, 17-ejector, 18-air compressor

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Experimental Approach of NIICHIMMASH

- Use full-scale injector elements
- Experiment designed to simulate controlling process - mixing
- Match equivalence ratio and volumetric flowrates using diluted gaseous propellants
- Combustor acoustics matched by using appropriately sized low-pressure chamber
- Stability boundaries determined by varying flowrates
- Relative boundaries indicate stability ranking

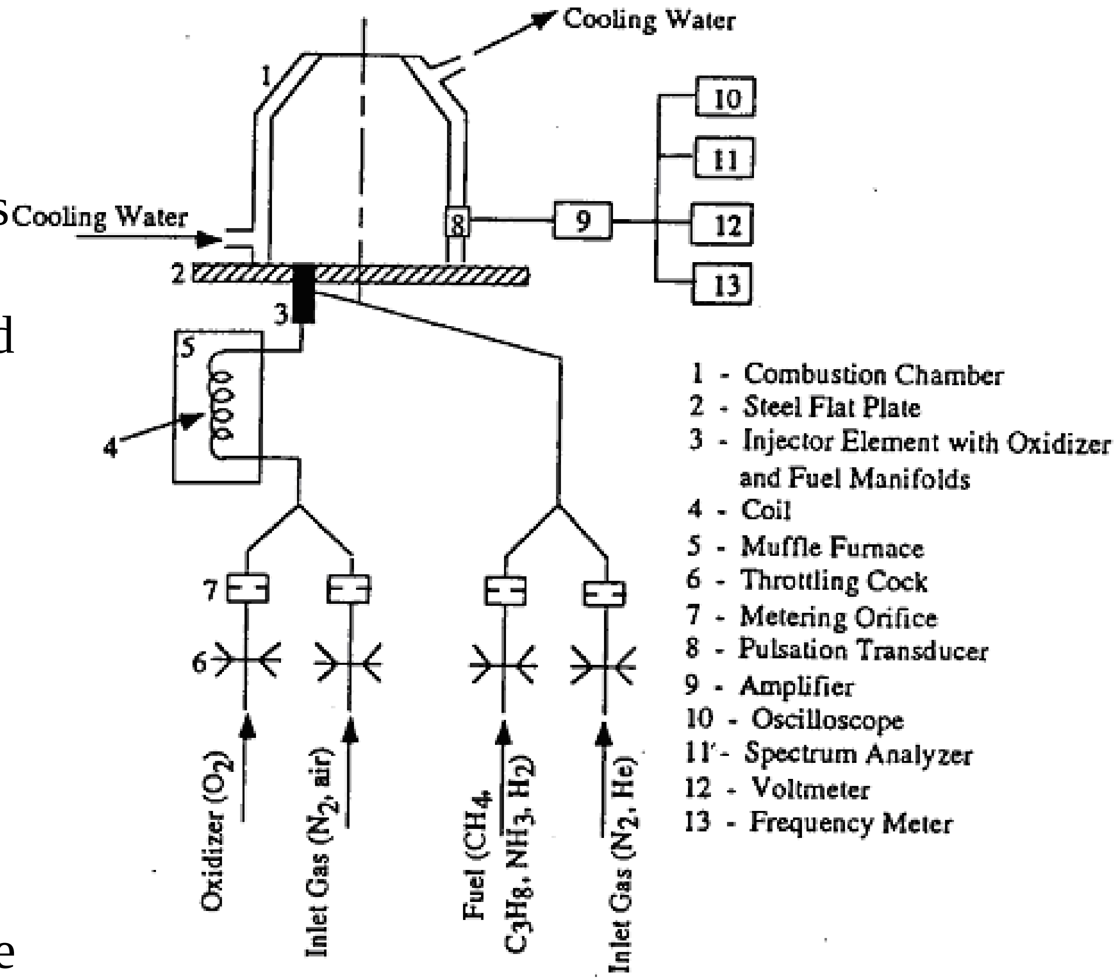


Figure 6. Schematic of Single Element Model Set-up and Instrumentation

Propellant Distribution Effects

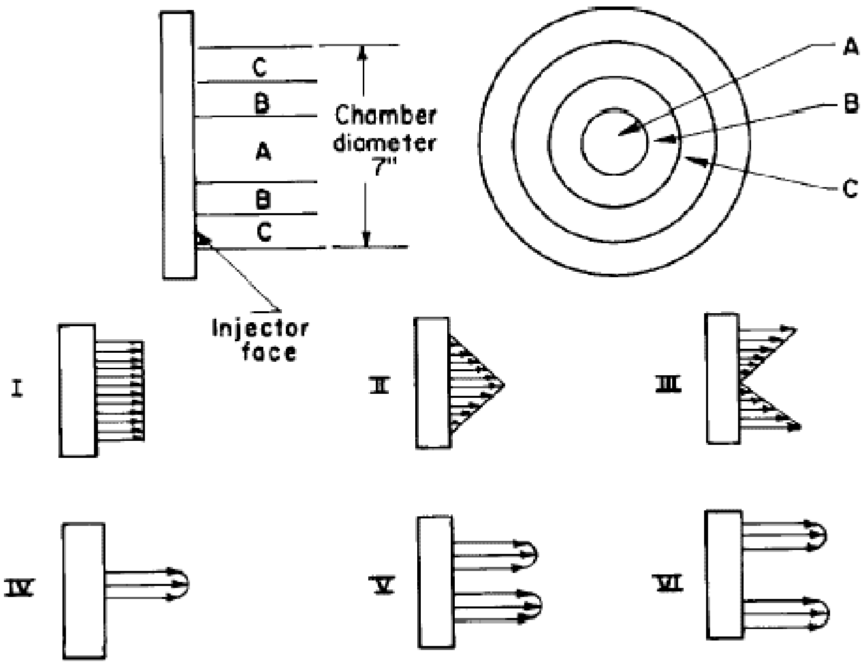


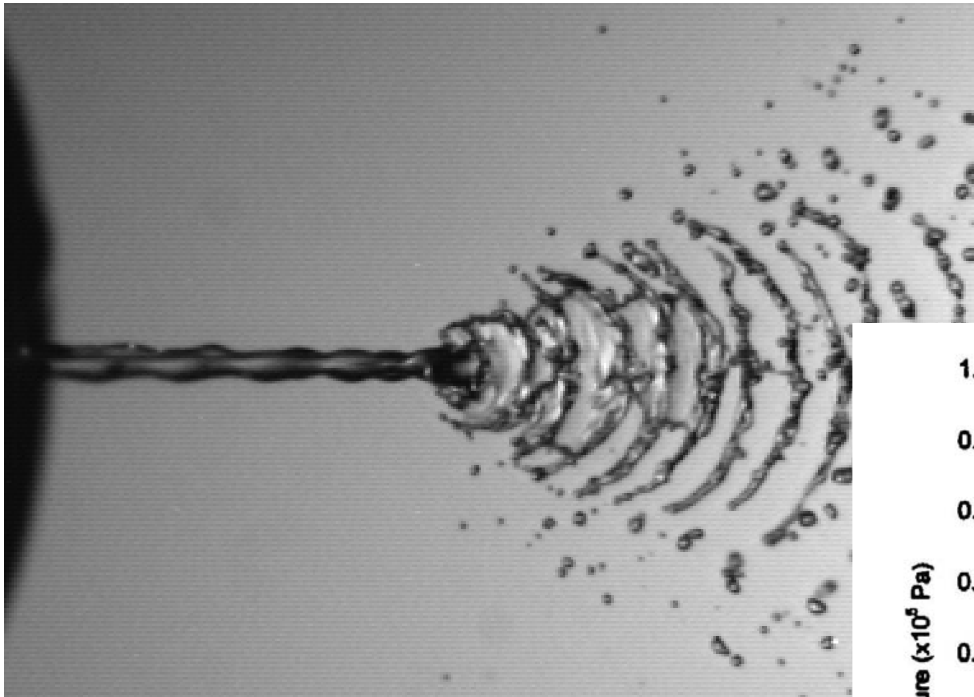
FIGURE 7.2.5a.—Injection radial profile comparison.

TABLE 7.2.5a.—GAS ROCKET TEST HISTORY WITH VARIOUS INJECTION PROFILES

[Instabilities initiated spontaneously and linearly; mean chamber pressure, 150 psia; combustion chamber diameter, 7 in.; combustion chamber length, 6 in.]

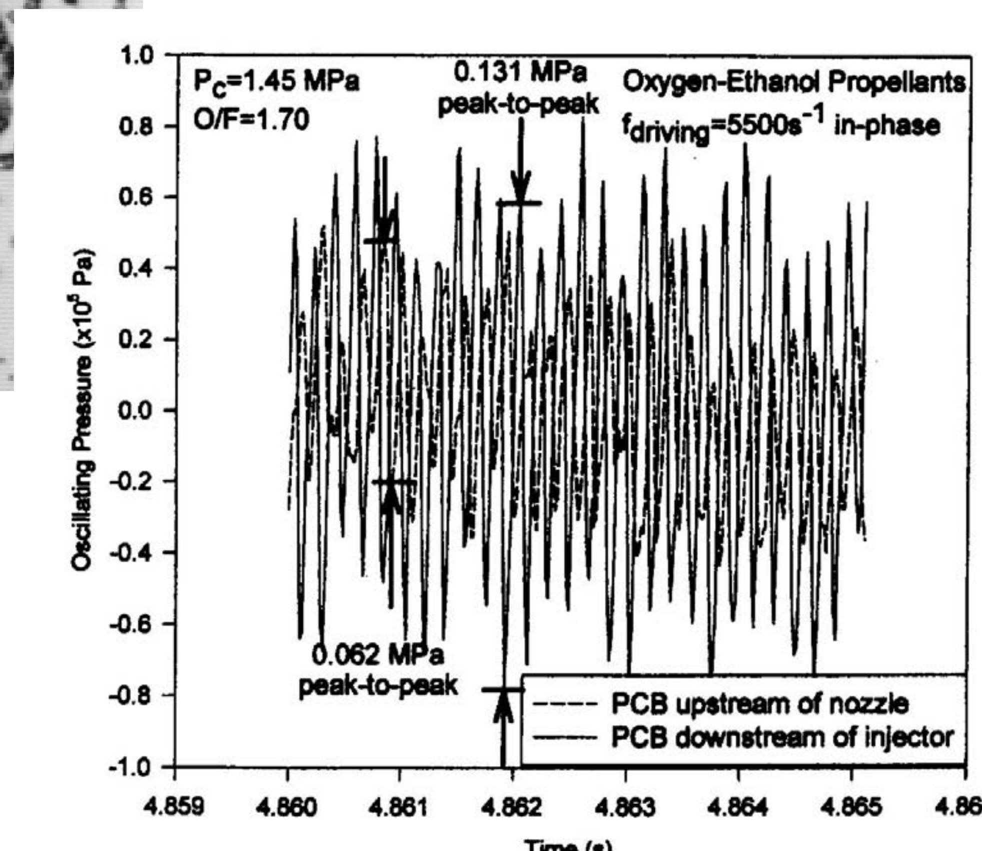
Profile	Amplitude, psi	Mode
I	7	1st tangential
II	0	Stable
III	11	1st tangential
IV	13	1st radial
V	0	Stable
VI	40	1st tangential

Single Element ‘Instability’

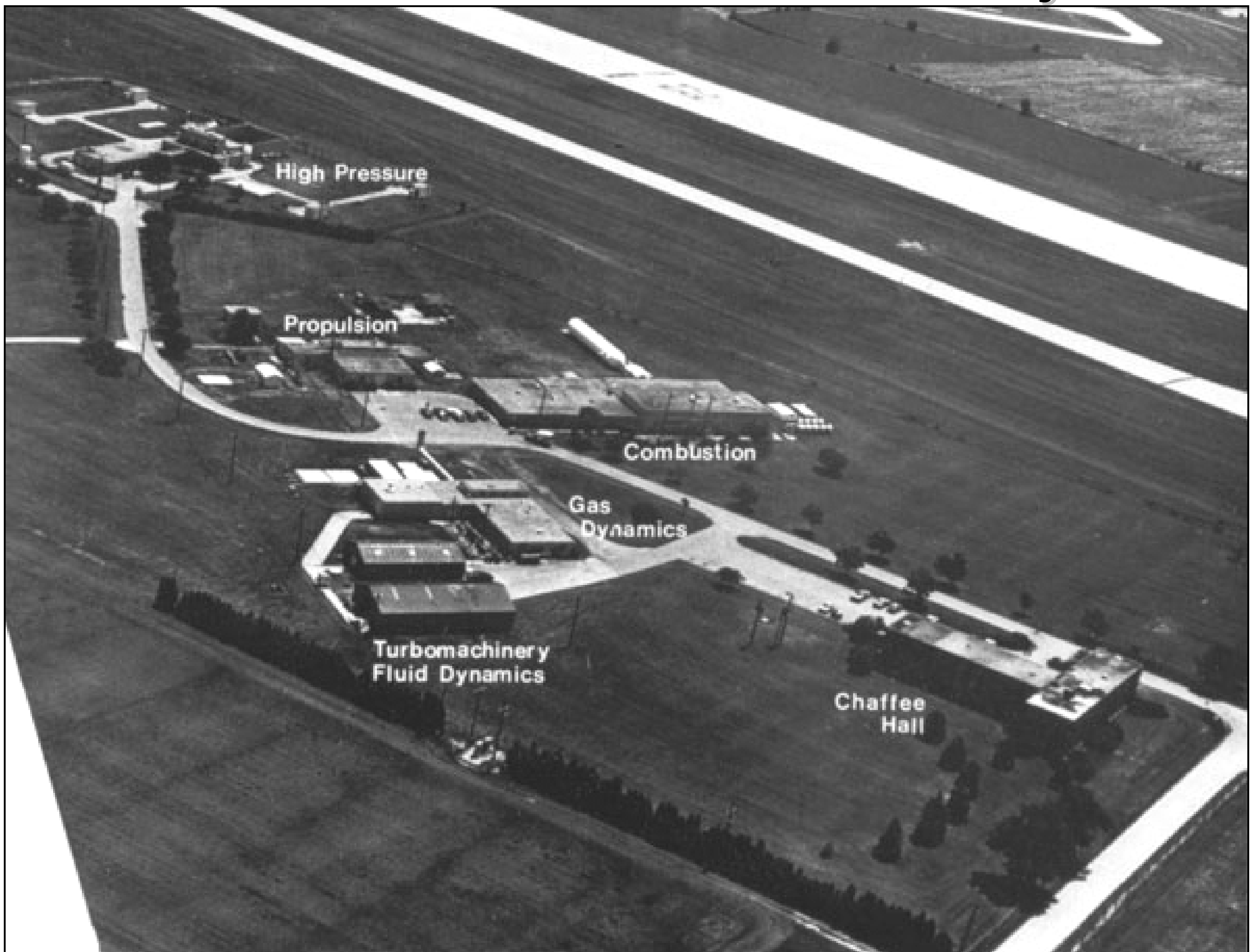


Impinging jets driven by piezoelectric actuator

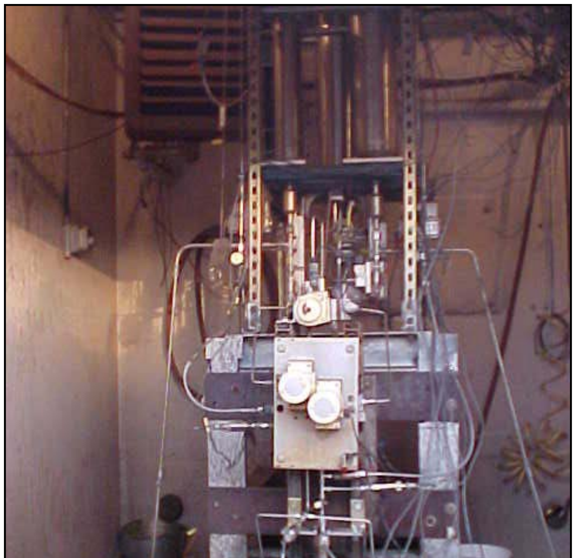
Combustor oscillations at driven atomization frequency



Subscale Test Activities at Purdue - Maurice Zucrow Laboratory



Advanced Propellants and Combustion Lab



- Two cells w/ 1 Klbf thrust stands
- Propellant supply of 1800 psia
- 2 - 4 gallon oxidizer tanks
- 1 & 4 gallon fuel tanks
- National Instruments hardware & LabView software
  - 32 channels pressure
  - 32 channels temperature

•All valves computer controlled

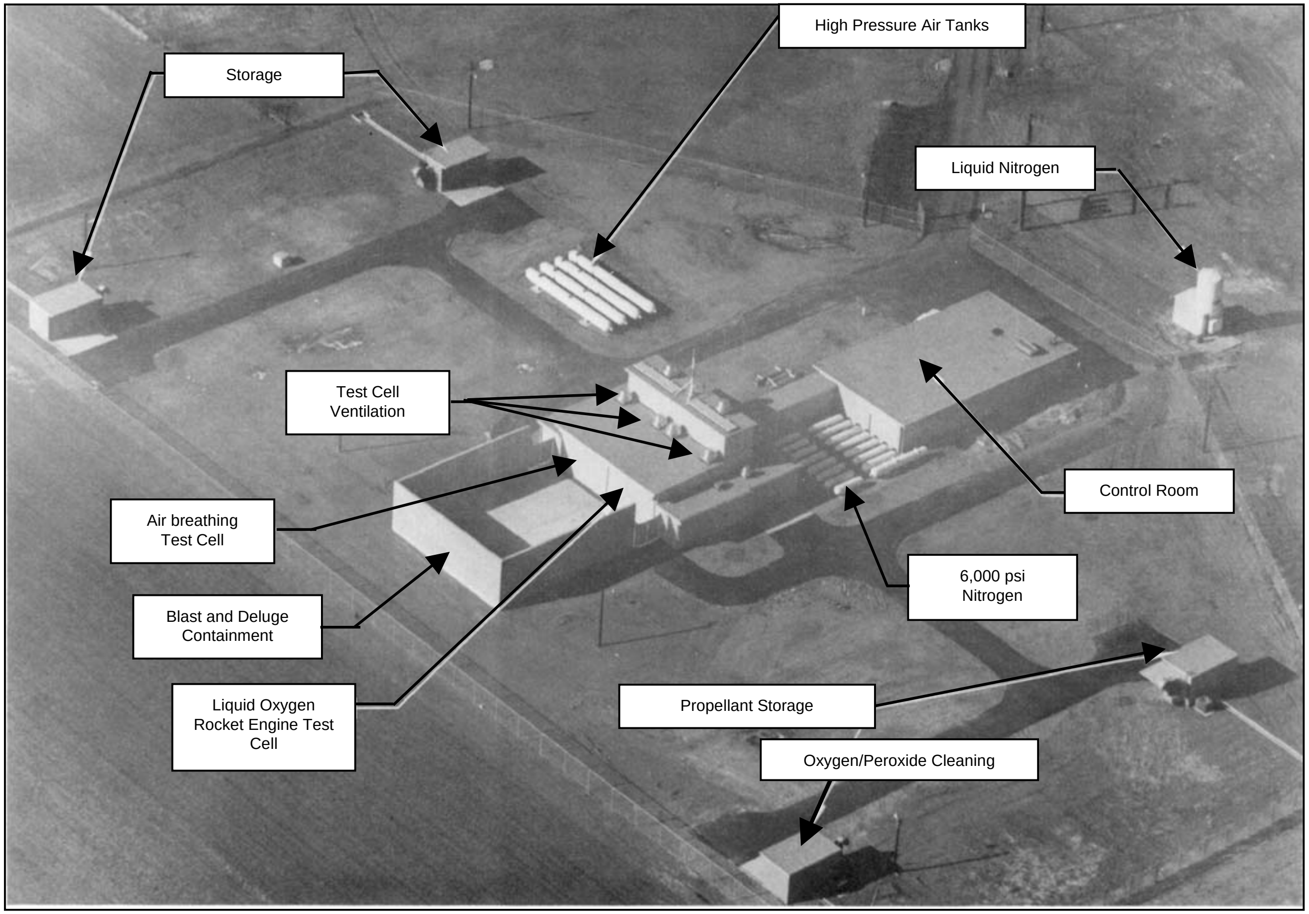
•Rapid test article installation

•Design/Build/Test course

High Pressure Lab

Renovation funded thru Indiana 21st Century R & T Fund – Propulsion and Power Center of Excellence

Facility activated in May ‘03



6,000 psi Nitrogen System

- Pressurization, Actuation and Purge Gas
- 2,400 gallon Liquid Nitrogen Tank w/ 6,000 psi Pump
- 253 ft^3 6,000 psi Nitrogen Tube Trailer
- Computer Controlled Pressurization Systems

Propellant/Coolant Tanks

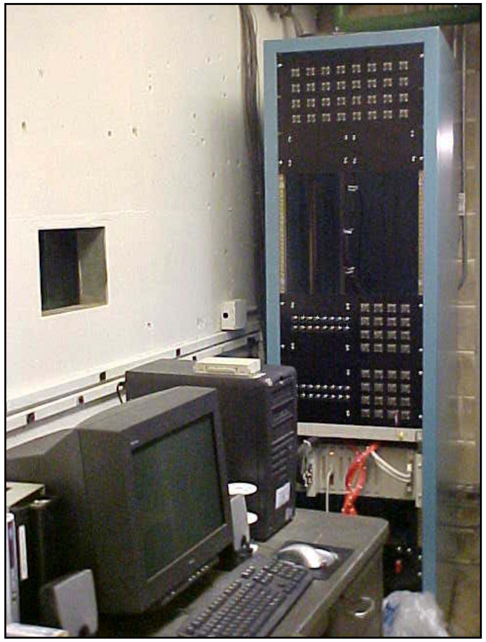
- 22 gal 5,000 psi LOx
- 16 gal 5,000 psi Fuel
- 220 gal 5,000 psi H_2O
- 400 gal 800 psi H_2O_2
- Hydraulic Control Valves

10,000 lbf Thrust Test Cell

- LabView 6.1-based DACS
- 10,000 lbf thrust measurement
- 64 channels pressure
- 96 channels thermocouples
- 18 channels analog control
- 32 channels on/off control

Control System Operation

- Data System Located Adjacent to Test Cell
- Operation Remoted to Control Room (KVM Extender) for Testing
- Video Recorded Directly to DVD



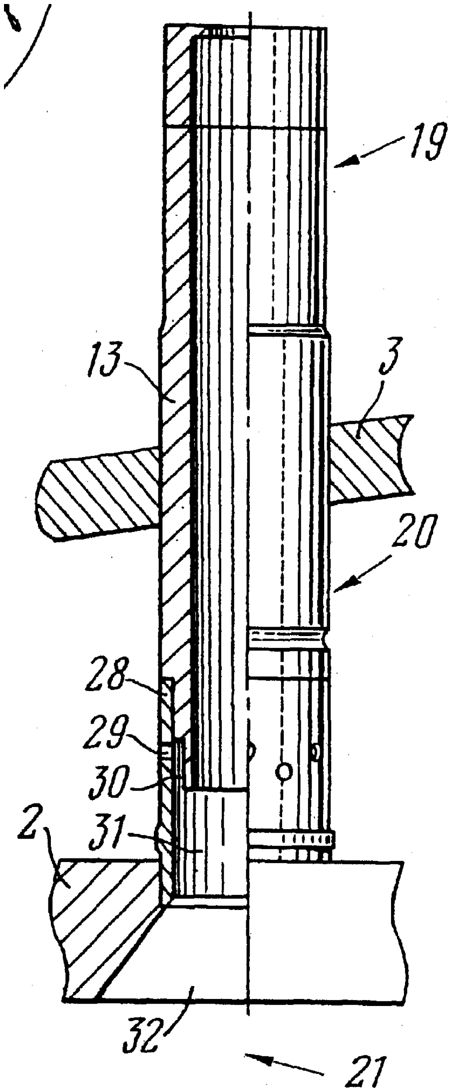
Test Cells

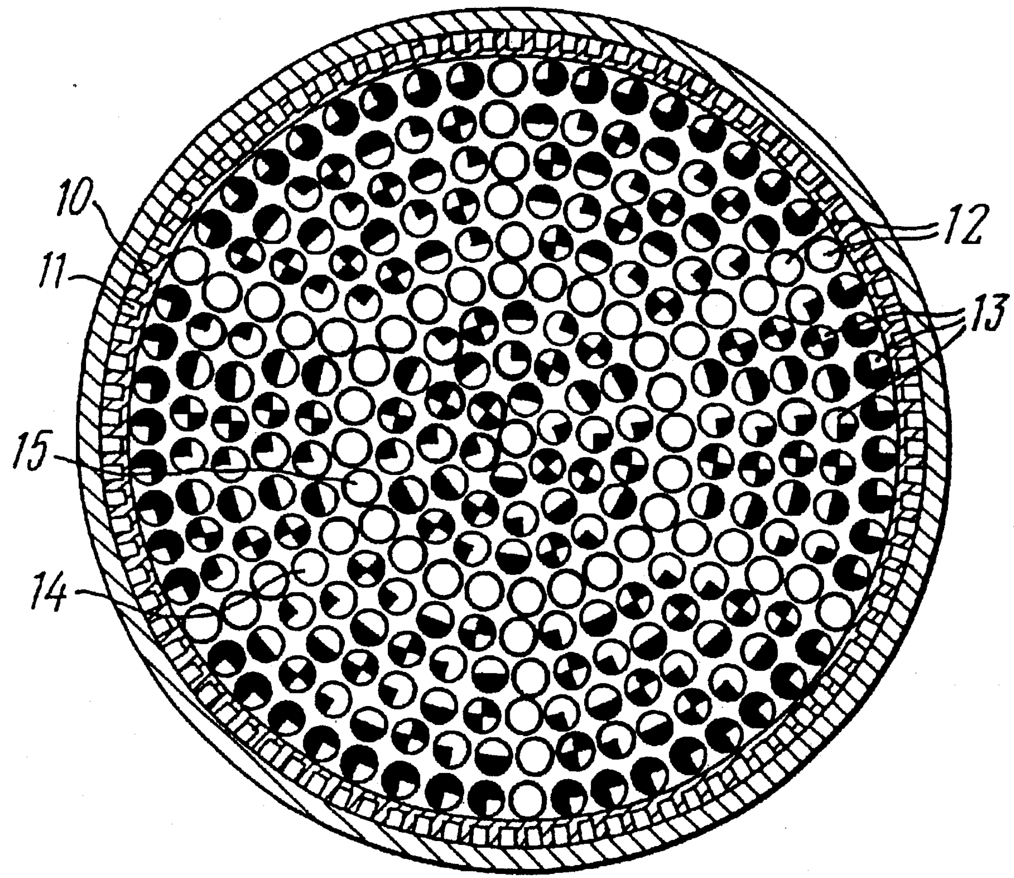
- 18” Thick Reinforced Concrete Test Cell Walls
- High Flow Capacity Test Cell Exhaust Fans
- Heated High Pressure Air Plumbed to Both Cells
- Walled Containment Area

Injector Characterization Scaling Approach

- Study Objectives
  - Steady state and dynamic characterization of ORSC MC injector elements
- Approach
  - Investigate full-scale elements at realistic operating conditions
  - No film cooling (if possible)
  - Evaluate different injector design configurations
  - Couple with analysis
- Measurements
  - Energy release profile from axial pressure gradient
  - Injector face and chamber wall thermal environments
  - Plume signature with IR tomography
  - Manifold, injector and chamber p’

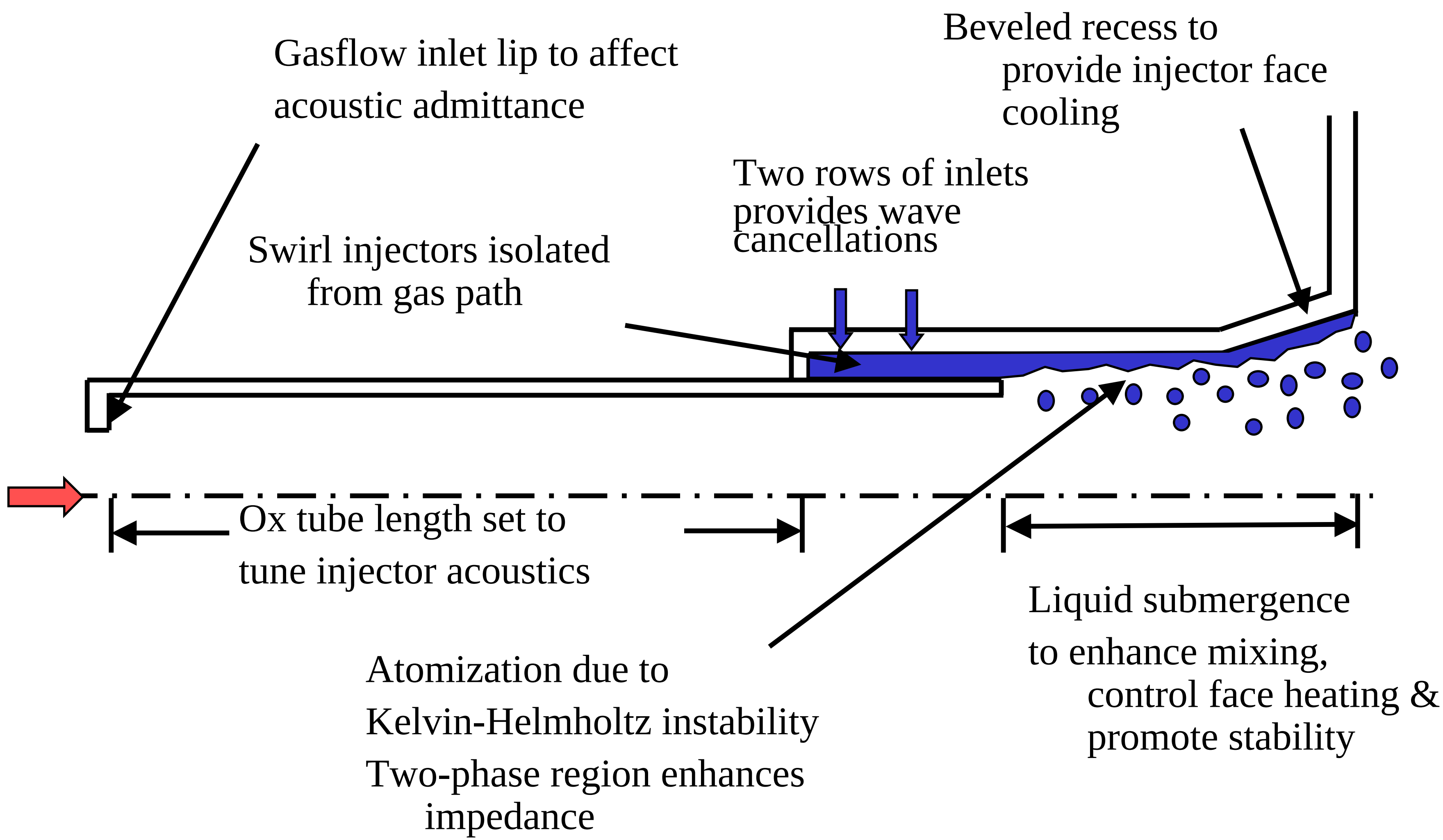
ORSC Main Combustor Components



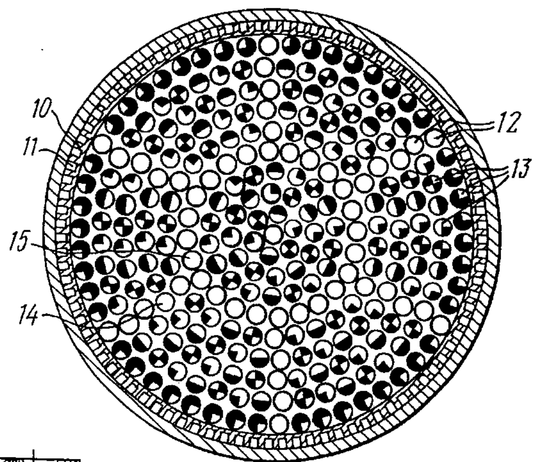


271 elements, 1722 lb_f each, d = 0.5 in

Principle Design Features



Single Element Sizing Exercise



Approach

- use full scale F/element (1722 lb_{fvac})

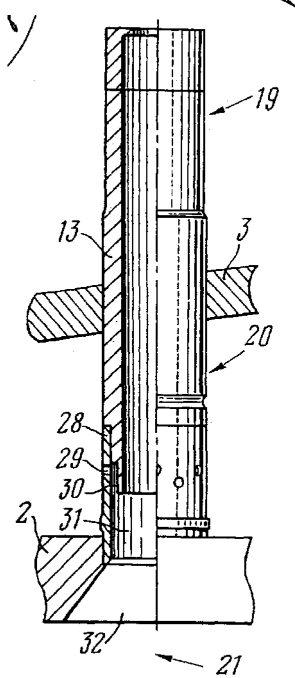
  ➡ mox = 3.6 lb/s, mf = 1.2 lb/s

- test at ‘full’ Pc (2250 psia)

  ➡ At = 0.39 in^2, dt = 0.70 in

- match injection pressure drops (10%)

  ➡ dinj, ox = 0.43 in, dinj = 0.57 in



Possible scaling methods:

Contraction ratio (1.61) ➡ dc = 0.89 in

Element to chamber area ratio (0.30) ➡ dc = 1.04 in

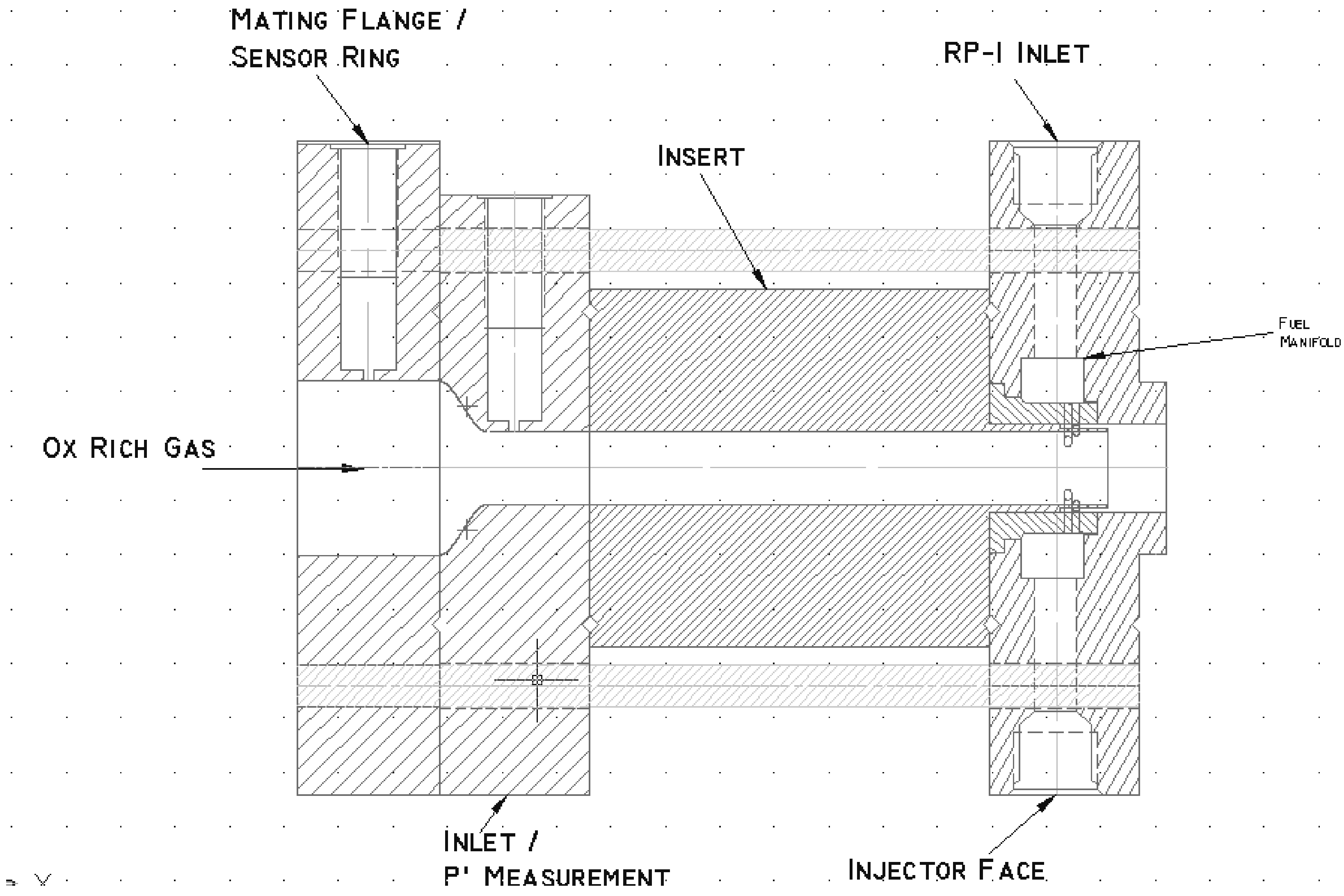
Element-element spacing (0.60d) ➡ dc = 0.91 in

Element-wall spacing (0.60d ?) ➡ dc = 0.91 in

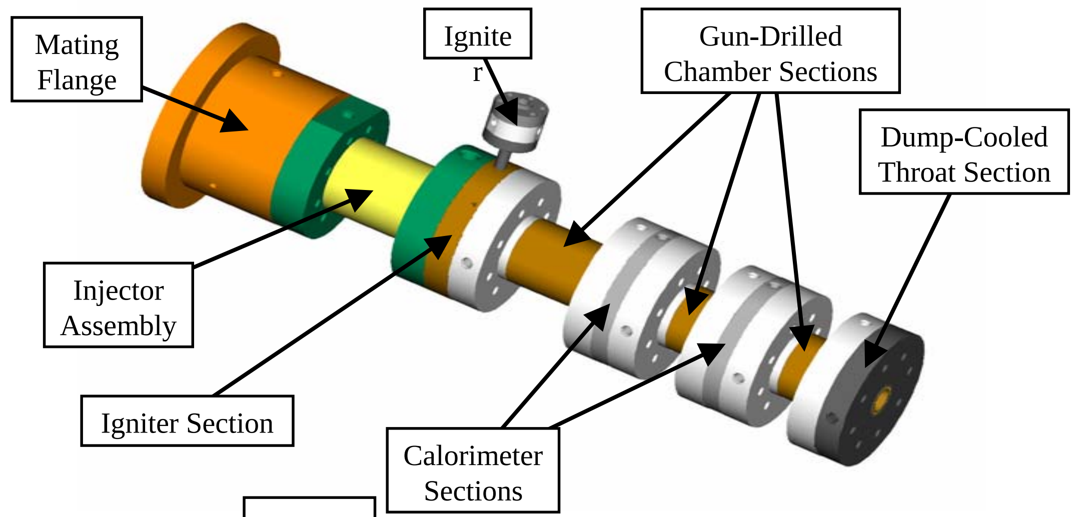
Element area (0.65 in^2) ➡ dc = 0.91 in

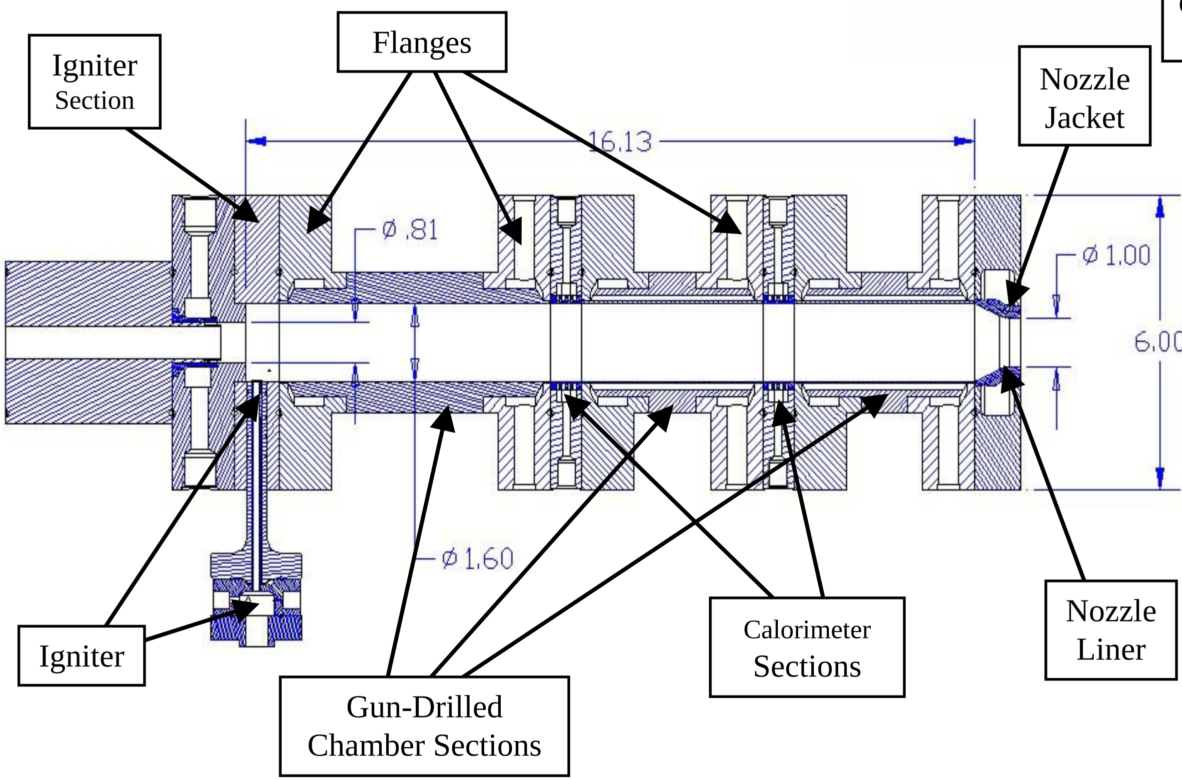
Chamber length based on L* ~ 30 in (??)

Baseline Injector Design



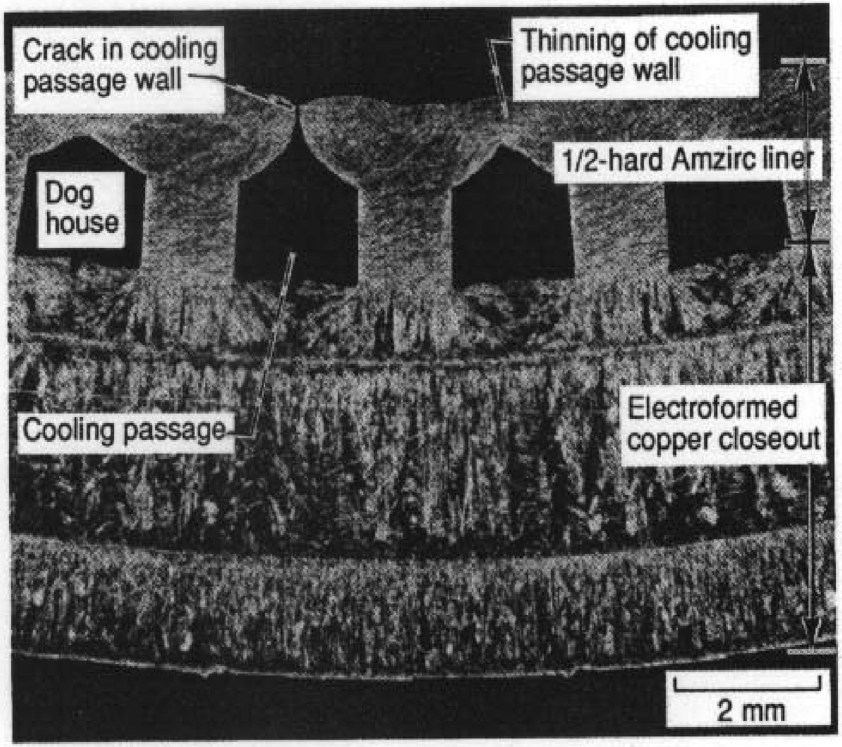
High-Pressure Chamber





Life Prediction - Background

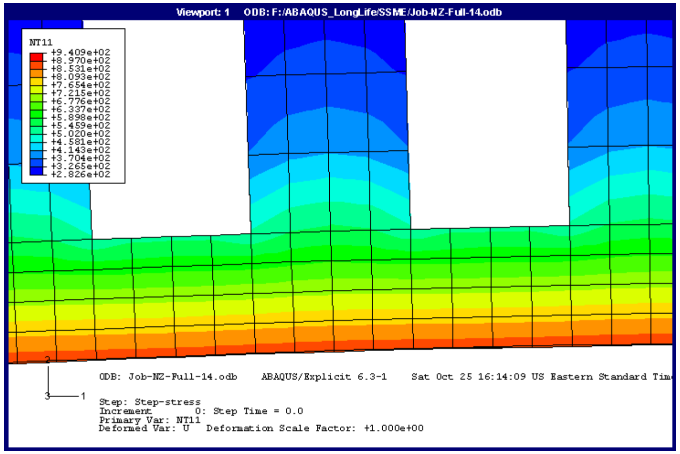
- Rocket combustor liner such as SSME operated at high temperature (6000F) and pressure (3000 psi) ranges as well as extreme heat flux (80 Btu/in^2-s) requires active cooling devices to prevent material failure.
- Combustor liner experiences high thermal structural stress (~100 MPa) during mission profile (SSME 8 min)
- Experiments by Quentmeyer and Jankovsky showed bulging and thinning of liner due to cyclic loading
- Kasper and Porowski developed analytical life prediction methods using simple fatigue and creep model
- Robinson, Arnold and Freed developed visco-plastic model for fatigue-creep interaction phenomena which is believed to be a main failure mechanism



Typical failure mode of combustor liner at throat so called “dog house effect” per Quentmeyer

Full Scale – Subscale Life Comparison

– Pc = 3300 psi, Tc = 3500 K



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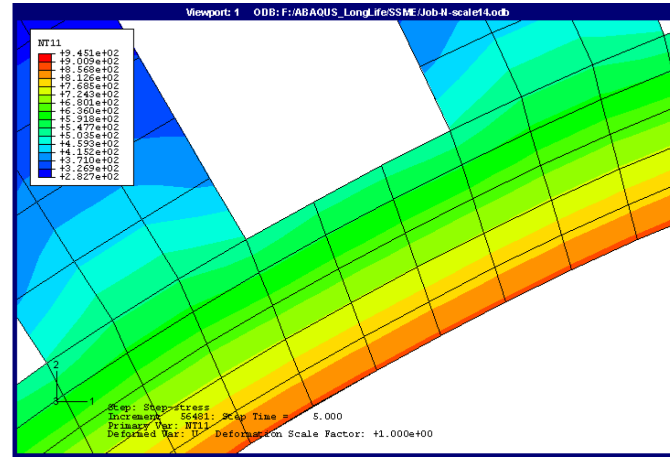

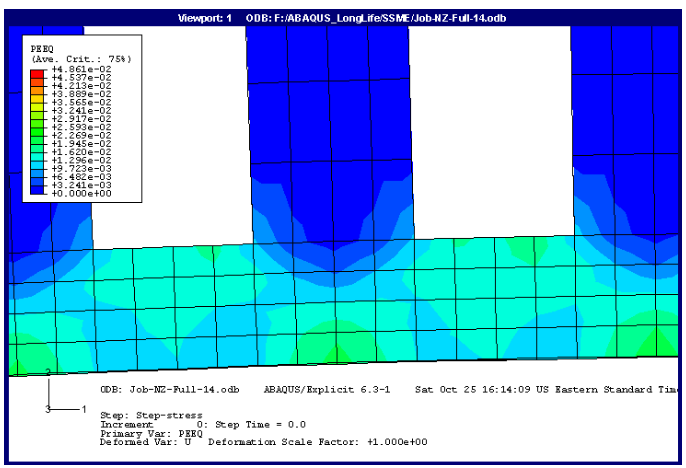

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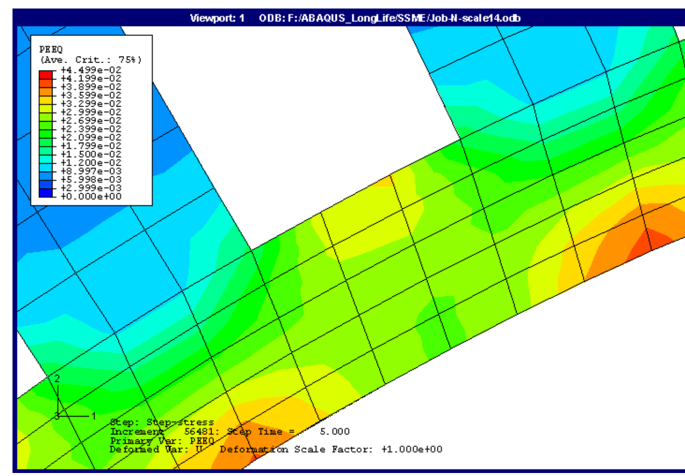


Full scale engine
Strain_max = 2.4
Life = 120

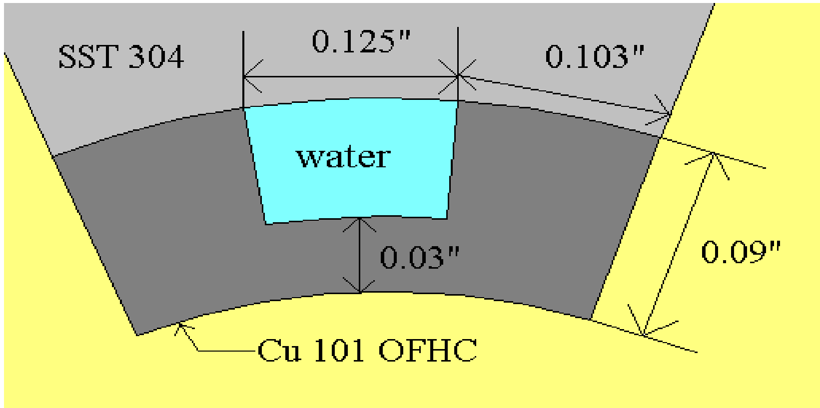
1/10 scale model
Strain_max = 3.94
Life = 48

Approach

- Develop DBT course with life prediction as part of AAE curriculum
- Develop design requirements
  - Controlled hot-gas environments – use ‘pre-combustor’
  - Creep-fatigue interaction failure of cooled liner
  - Failure within reasonable number of cycles
- Life prediction analysis using conventional methods
  - Chemical equilibrium in pre-combustor
  - One-dimensional heat transfer analysis for initial design
    - critical heat flux and cooling requirements, duty cycle
  - FEM for stress and plastic strain
  - Strain-life curves for cycle life
  - More advanced life modeling by graduate student following project
- Cyclic testing of test article
  - Ten cycles per test
  - Validation of cooling analysis
  - Regular inspection
- Test-to-failure

Combustor Design Parameters

- Top level requirements
  - Less than 200 life cycle
  - Test should produce verifiable results
  - Liner has no melting prior to the LCF failure
  - All parts had to be manufactured in ASL at Purdue
- Under these requirements, the coolant pressure, flow rate and cooling channel aspect ratio (0.5) were determined.



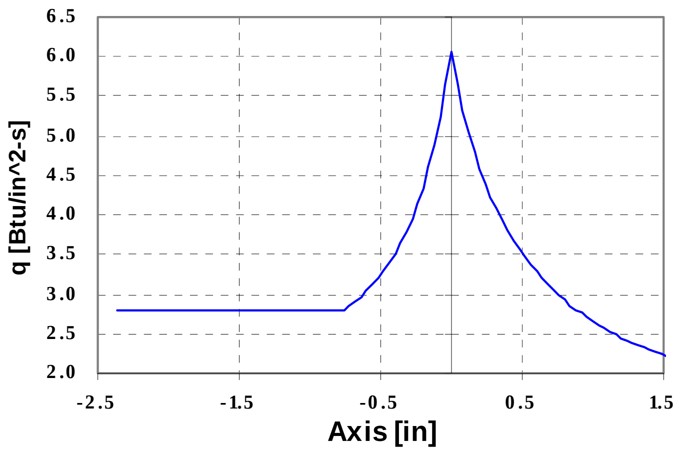
Parameter	Value
Propellant	90% H_2O_2 + JP-8
Propellant mixture ratio (O/F)	4.0
Propellant flow rate	1.25 lb/s
Chamber pressure (P_c)	200 psia
Chamber temperature (T_c)	3440 °F
Characteristic velocity (C*)	4961 ft/s
Throat area (A_t)	0.915 in^2
Characteristic length (L*)	70
Test liner diameter	2.0 in
Test liner length	5.0 in
No. of cooling channel	30
$P_{coolant}$	110 psi
$M\_dot_{coolant}$	0.8 lb/s

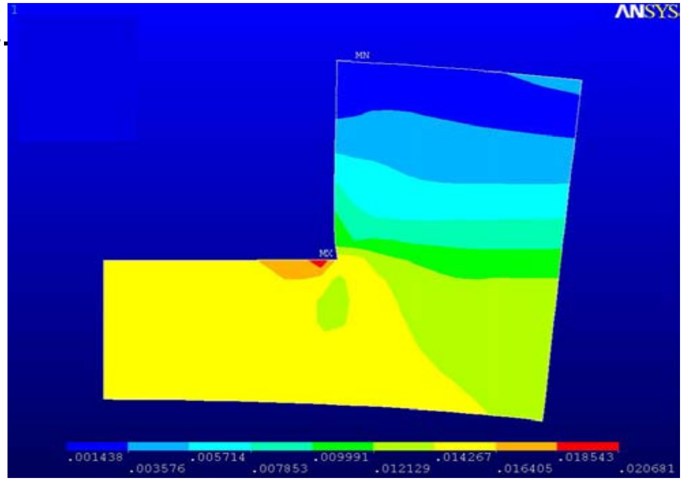
Table 1 : Combustor design parameters

Thermal Structural Prediction

Thermal analysis

- Burn out heat flux --- 6.54 Btu/in^2-
- Max wall temp --- 670 K

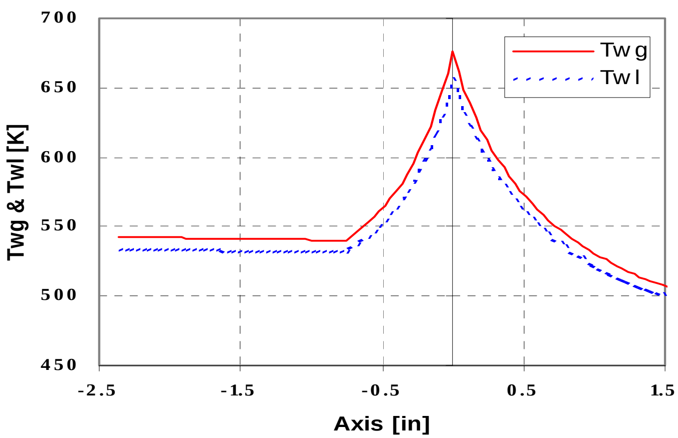


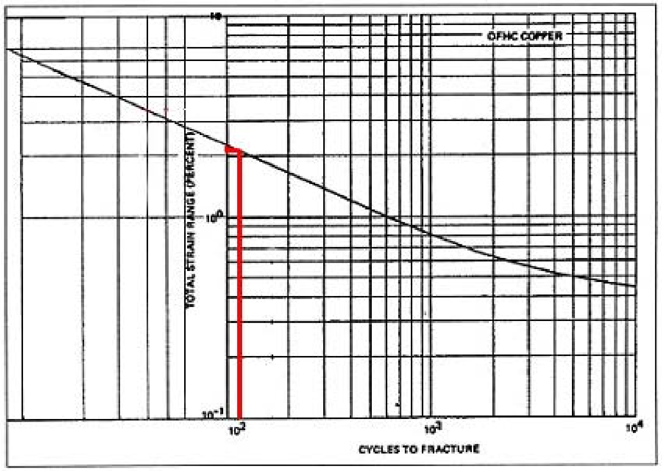


Total strain predicted by ANSYS around rectangular cooling channel.

-Total strain --- 2.0 %

-Life expected --- 115 cycles

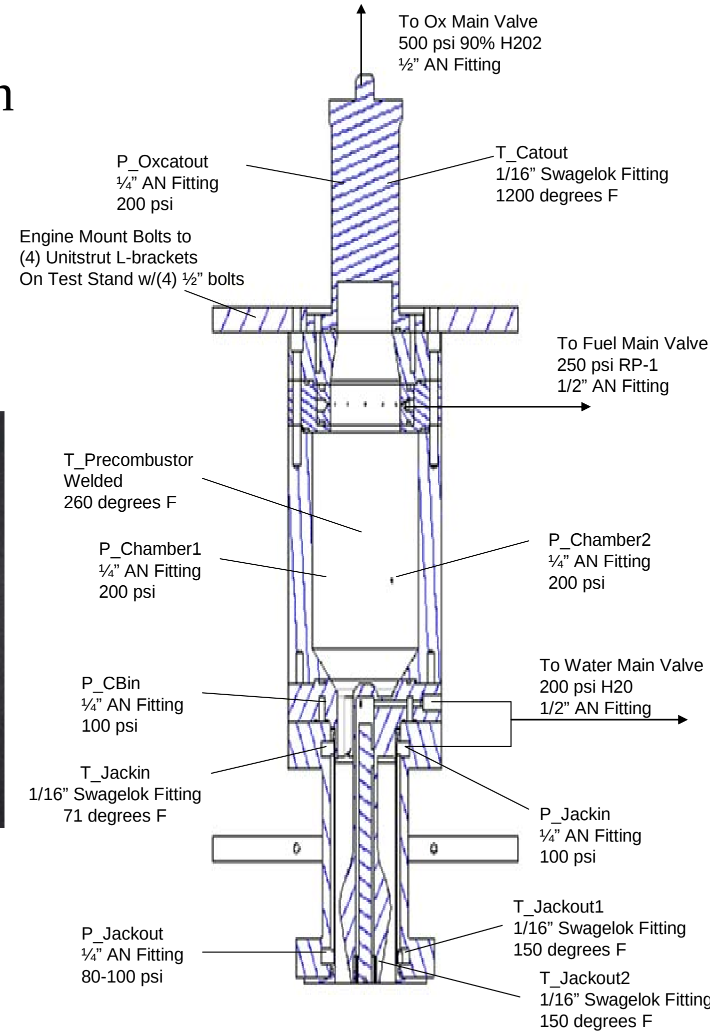




Strain-life curve for OFHC at 810 K from NASA CR-134806, 1975

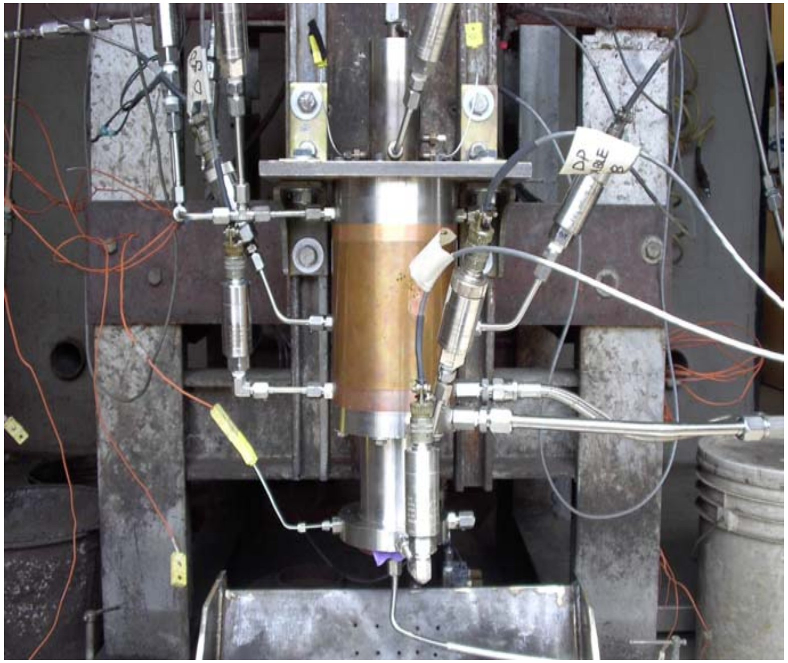
Test Article

- Catalyst bed for decomposing H_2O_2
- Heat sink dump combustor for hot gas generation
- Chamber liner --- water cooling
- Center body --- water cooling with TBC (0.01” thick)



Testing

- Tests were conducted in the APCL at Purdue University
- Propellant flow timing sequence was automatically controlled by pneumatically actuated valve with LABVIEW system

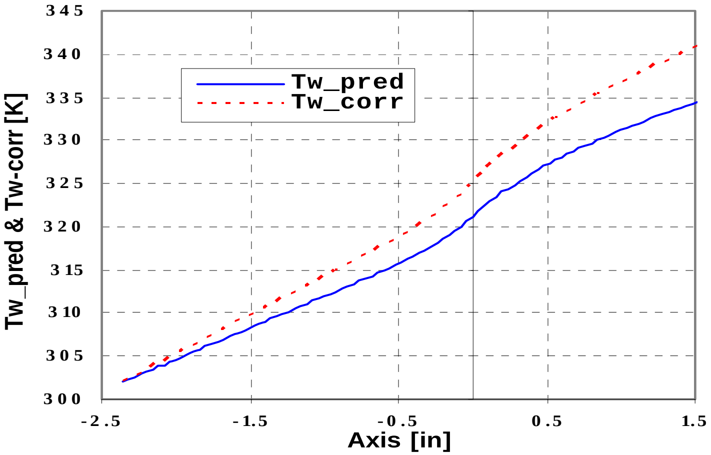


Test article assembly on test stand

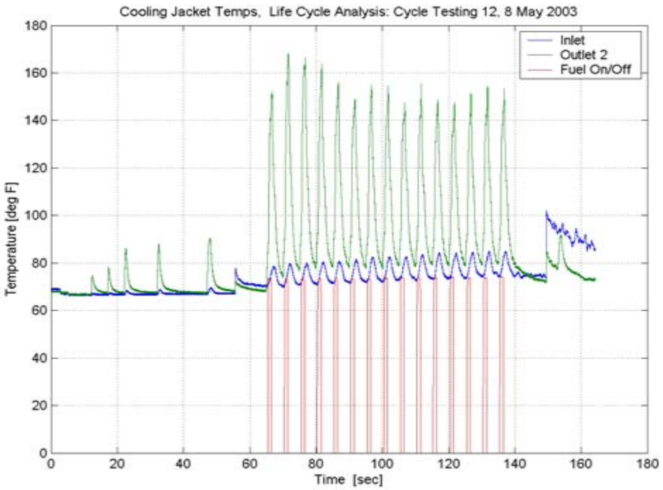
Cyclic test

Test Results

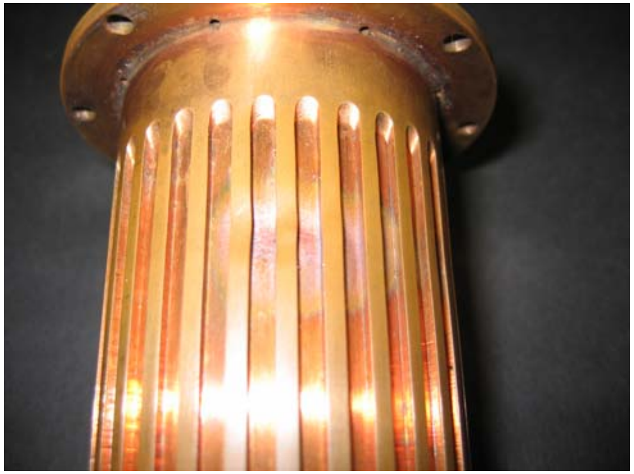
- Chamber pressure, C* efficiency, propellant mass flow rate, coolant temperature and pressure were measured and calculated
- Data reduction was performed using in-house code written by students using MATLAB
- Validation procedure
  - Measure coolant ΔT, wall thinning rate
    - 2.15E-5 in/cycle (0.032”→0.029”)
  - Verify 1D thermal model
  - Compute updated thermo-structural environment
  - Make life prediction



Predicted and measured coolant temperature
ΔT = 4.0K at throat



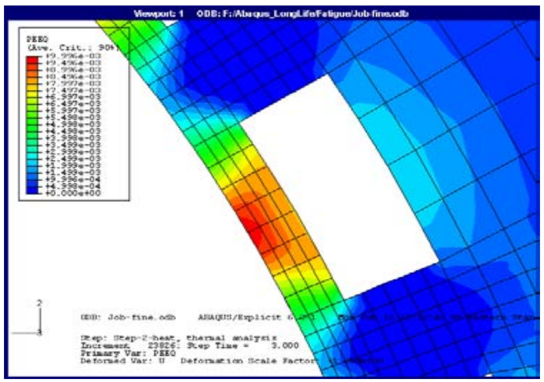
Coolant temperature



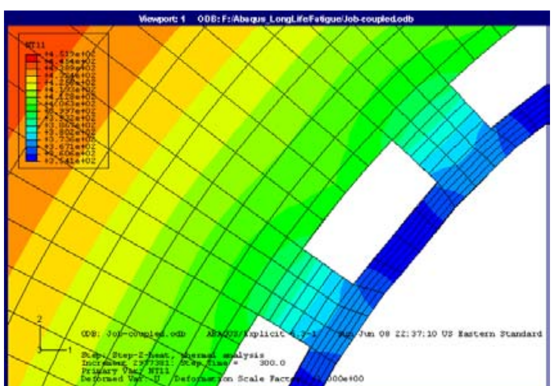
Discoloration and deformation at 90 cycles (1.5”×0.6”)

Updated Structural Analysis

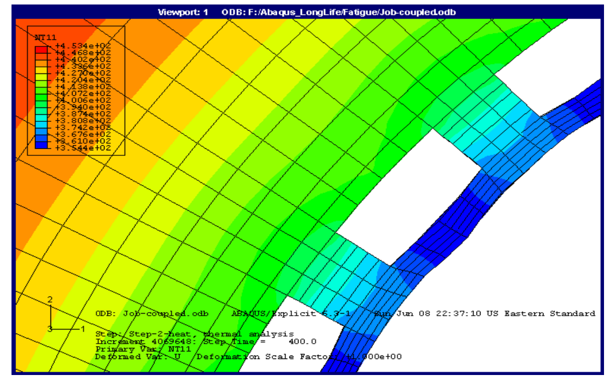
- Simulation of temperature, strain and deformation (bulging, thinning) using ABAQUS explicit module
- Maximum strain : 1.2 % at middle of ligament
- Only bulging of ligament was simulated



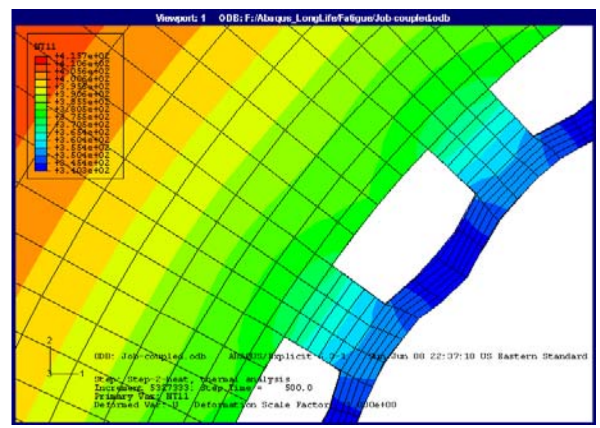
Plastic strain distribution



Deformation after 60 cycle



Deformation after 80 cycle



Deformation after 100 cycle

Summary and Conclusions

- Small-scale rocket combustor was designed and tested to verify life prediction models for low cycle fatigue and fatigue-creep interaction.
- Several life prediction methods were applied to predict combustor life and were compared with test results.
- Correlation data used to improve predictions.
- Improvements would include fixing the liner lands to the structural jacket, and testing at more severe conditions.

Prediction method	Estimated life cycle	Determined life cycle by experiment
Effective stress-strain	**115**	
ANSYS	**115**	
Porowski	**51**	**270**
Dai and Ray with Freed model	**260**	
ABAQUS	**320**	

Comparison of life prediction with test

Summary and Conclusions

- 100’s of cycle goal is very challenging and verification would be very expensive
  - Question of economic feasibility
- Improved life prediction methodology for expanding range of design and operational scenarios is needed
  - Probabilistic life prediction design analysis
  - Testing methodologies with *in situ* thermostructural response measurements
  - Environments definition
  - Improved material database and understanding of damage mechanisms

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